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The CYGNO experiment, a directional detector with optical readout for Dark Matter search(*)

F. D. Amaro(1), R. Antonietti(2)(3), E. Baracchini(4)(5), L. Benussi(6), S. Bianco(6), F. Borra(7)(8), C. Capoccia(6), M. Caponero(6)(9), D. S. Cardoso(10), G. Cavoto(7)(8), I. A. Costa(2)(3), E. Dané(6), G. Dho(4)(5), F. Di Giambattista(4)(5), E. Di Marco(8), G. D'Imperio(8), F. Iacoangeli(8), H. P. Lima Júnior(11), E. Kemp(10)(4), G. S. P. Lopes(12), G. Maccarrone(6), R. D. P. Mano(1), R. R. Marcelo Gregorio(13), D. J. G. Marques(4)(5), G. Mazzitelli(6), A. G. McLean(13), P. Meloni(2)(3), A. Messina(7)(8), C. M. B. Monteiro(1), R. A. Nobrega(12), I. F. Pains(12), E. Paoletti(6), L. Passamonti(6), S. Pelosi(8), F. Petrucci(2)(3), S. Piacentini(7)(8), D. Piccolo(6), D. Pierluigi(6), D. Pinci(8), A. Prajapati(4)(5), F. Renga(8), R. J. d. C. Roque(1), F. Rosatelli(6), A. Russo(6), J. M. F. dos Santos(1), G. Saviano(6)(14), N. J. C. Spooner(13), R. Tesauro(6), S. Tomassini(6), S. Torelli(4)(5) and D. Tozzi(7)(8)

(1) *LIBPhys, Department of Physics, University of Coimbra - 3004-516 Coimbra, Portugal*
(2) *Dipartimento di Matematica e Fisica, Università Roma TRE - 00146, Roma, Italy*
(3) *Istituto Nazionale di Fisica Nucleare, Sezione di Roma Tre - 00146, Rome, Italy*
(4) *Gran Sasso Science Institute - 67100, L'Aquila, Italy*
(5) *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso 67100, Assergi, Italy*
(6) *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati 00044, Frascati, Italy*
(7) *Dipartimento di Fisica, Università La Sapienza di Roma - 00185, Roma, Italy*
(8) *Istituto Nazionale di Fisica Nucleare, Sezione di Roma - 00185, Rome, Italy*
(9) *ENEA Centro Ricerche Frascati - 00044, Frascati, Italy*
(10) *Centro Brasileiro de Pesquisas Físicas - Rio de Janeiro 22290-180, RJ, Brazil*
(11) *Universidade Estadual de Campinas - Barão Geraldo, Campinas 13083-970, SP, Brazil*
(12) *Universidade Estadual de Campinas, UNICAMP - Campinas 13083-859, SP, Brazil*
(13) *Universidade Federal de Juiz de Fora, Faculdade de Engenharia - 36036-900, Juiz de Fora, MG, Brazil*
(14) *Dipartimento di Ingegneria Chimica, Materiali e Ambiente, Sapienza Università di Roma 00185, Roma, Italy*

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Summary. — The CYGNO experiment employs a gaseous Time Projection Chamber (TPC) in conjunction with Gas Electron Multipliers (GEMs) for amplification and optical readout. This configuration holds the potential to achieve precise 3D tracking down to O(1 keV) energies. The primary objective of this novel technique is to enable direct directional measurements of Dark Matter within our Galaxy. We assess the performance of the largest prototype, LIME, at Laboratori Nazionali del Gran Sasso (LNGS), including stability, energy response and resolution, using radioactive X-ray sources and Monte Carlo simulations. These findings will guide the fine-tuning of the CYGNO_04 demonstrator.

1. – The CYGNO Project

Determining the nature of Dark Matter (DM) represents a significant challenge in contemporary physics. Weakly Interacting Massive Particles (WIMPs) are a compelling candidate for DM, and they are thought to elastically interact with conventional matter on Earth, resulting in nuclear recoil (NR) events. A promising area of research involves searching for a directional signature of low-energy NRs, which are expected to a exhibit a peculiar dipolar angular distribution peaked in the opposite direction of the Cygnus constellation [1].

The CYGNO experiment aims to directly detect DM by employing a gaseous time projection chamber (TPC) equipped with a triple-GEM (Gas Electron Multiplier) amplification stage and utilizing an optical readout approach. The experiment operates at atmospheric pressure and room temperature [2]. The choice of the gas mixture, He:CF_4 in a 60/40 ratio, is motivated by its large scintillation yield that aligns with the quantum efficiency (QE) of the main optical sensor. Furthermore, the low mass of helium enables more efficient momentum transfers with low-mass WIMP-like particles.

In LIME, when charged particles interact within the gas volume, ionization electrons are produced and drifted along an electric field toward the triple GEM stack for amplification. The secondary scintillation light produced during the electron avalanche is captured by a scientific CMOS camera (sCMOS), recording the light emission pattern on the GEM plane. Additionally, photomultiplier tubes (PMTs) are employed to measure the topology of the tracks in the orthogonal direction of the GEM plane, allowing a 3D reconstruction. Several prototypes have been constructed and are currently studied in preparation for the ultimate goal: creating a modular O(1 m^3) CYGNO_04 demonstrator at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN to demonstrate the feasibility of this experimental approach.

2. – The LIME prototype

The LIME detector, a 50-liter TPC, is the largest prototype developed to date [3]. A triple 33x33 cm^2 GEM stack amplifies the ionization charge produced in a 50 cm-long drift region. A high-resolution sCMOS camera and four PMTs around it capture the secondary scintillation light. The camera with 2304x2304 pixels is equipped with a Schneider lens, resulting in each pixel covering an area of 152x152 μm^2. The sensor is

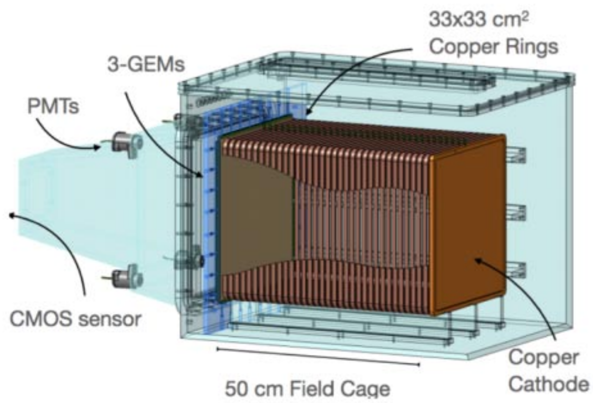

Fig. 1. – Illustration of LIME: A depiction showcasing square-shaped copper rings employed in constructing a field cage that is sealed on one end by the triple-GEM stack. The positions of four PMTs and a CMOS optical sensor are marked. An acrylic gas vessel encloses both the field cage and the GEM stack.

chosen for its low noise level, around one photon per pixel, and for its quantum efficiency of 80% at 600 nm, matching the spectral emission of the He:CF_4 mixture [4]. The camera and PMTs not only allow direction sensitivity but also enables the fiducialization of the sensitive volume to reduce the background. LIME underwent testing using multiple X-ray sources at the INFN Laboratori Nazionali di Frascati (LNF). Over a month of operation, the detector maintained stable conditions, with a rate of current spikes lower than 2.7 per hour, confirming the feasibility of continuous underground operation. The energy resolution, determined using a ^{55}Fe source emitting 5.9 keV X-rays at varying distances from the GEM plane, was measured constantly at about 14%. The detector performance was also evaluated using other various radioactive X-ray sources with energies ranging from 4 keV to 37 keV. This investigation revealed a consistent behavior across the entire energy spectrum.

3. – Monte Carlo simulation

To simulate the electronic recoils (ERs) and NRs observed in the sCMOS detectors, a Monte Carlo (MC) simulation of the detector response is used. Initially, the ionization energy deposits in the sensible volume are computed with GEANT4 [5] or SRIM [6] for ER or NR respectively. The detector response is then simulated by including the following effects: ionization electron yield, primary electron loss due to absorption along the drift, diffusion within the drift region and GEMs, charge amplification, gain saturation, photon emission and collection efficiency. The simulation output consists of a 2D image, which is subsequently analyzed using a custom reconstruction code based on DBSCAN [7]. A comparison between the tracks generated by simulated 5.9 keV ERs and actual ^{55}Fe data reveals an agreement within 10% across different GEM gain values and different position of the source. Preliminary investigations into the linearity of X-ray data and MC simulations also indicate a similar agreement.

4. – LIME and CYGNO Advancements

In early 2022, the LIME prototype was relocated underground at the LNGS, with the main objective of assessing the detector performance in low-radioactivity and minimal pile-up environment.

A comprehensive simulation has been conducted to predict background events, considering the internal radioactivity of the detector materials, as well as the ambient gamma and neutron flux. The implementation of fiducial cuts within the sensitive volume shows that a reduction of 96% reduction in radioactivity-induced background events. The same simulation has been used to design the best shielding configuration: 10 cm of copper to protect against gamma radiation, and 40 cm of water to screen against neutrons.

LIME, in its final run underground at the end of 2023, will measure the spectrum of fast environmental neutrons. This data will be of great importance to all experiments at LNGS seeking rare events.

Overall, LIME represents a crucial milestone in the progression toward the CYGNO_04 demonstrator, showcasing the potential for these techniques to be applied at a larger scale.

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